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THE TRANSFORMATION OF AN ALLOY CAST STEEL WHILE COOLING

*by C. R. Genung**

The problem of how to obtain maximum hardness and toughness in quenched and tempered steels throughout a wide range of metal sections is as critical today as it was at its inception. It is true that "austempering" and "martempering" have, to a certain extent, solved this problem for present-day heat treaters. However, in those shops where salt baths are not available, or where the size of castings limits their use, little else has been done to ease the situation. With the increased demand for higher tensile and impact properties, full hardening becomes a necessity rather than a desirability.

Confronted daily with this problem, it was decided to initiate an intensive study of the two basic phases of heat treatment: The Time-Temperature-Transformation Diagram and the Jominy End Quench Hardenability Test. Research projects, by many other workers, were also utilized in this study. The results are, it is felt, a unique approach to heat treatment.

S Curves

The time-temperature-transformation curve, or S curve, first developed by Davenport & Bain (1), and used as a basis for many research studies of heat treating, is an important guide to heat-treating procedure for many carbon and low-alloy steels. However, upon closer examination of this chart several other, and possibly more important, facts come to light:

1. The composition of the steel has little to do with the nature of the transformation product. The products formed are peculiar to the temperature at which they are found.

2. Elements, which are known to increase the hardenability, greatly lengthen the time at which austenite begins to change to another structure. The time may be increased ten-fold or even a hundred-fold over that required for a plain-carbon steel.

3. The shape of the transformation curve is altered as the hardenability increases so that pearlite is formed only with difficulty, the preference being toward harder and stronger structures which form at lower temperatures.

4. The transformation from austenite to other structures is not instantaneous. Completion of the reaction may take minutes, hours, or even days, depending upon the particular alloy studied, the phase in question, and the temperature at which it is formed.

These four observations, often overlooked in the eternal search for the ideal heat treating procedure, can be invaluable in developing optimum hardness and toughness in a low-alloy steel.

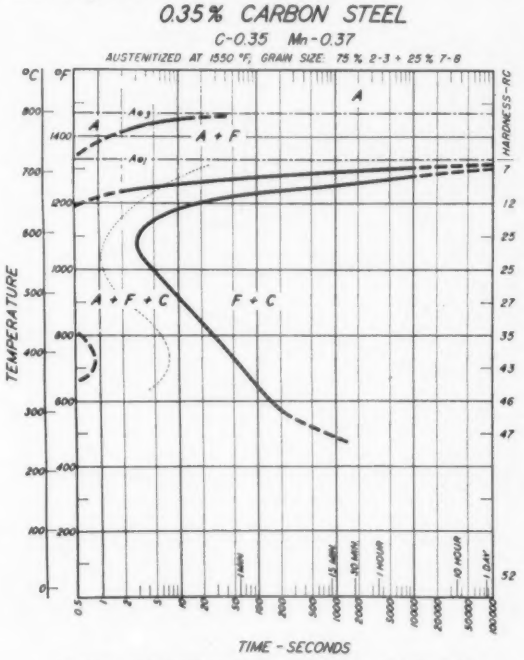


Figure 1—Transformation curve for a carbon steel

The fact that, experimentally, the transformation takes place at constant temperature levels, detracts in no way from the usefulness of the work. Certain microstructures form at known holding temperatures, provided the dwell at that temperature is long enough for completion of the transformation. These structures are peculiar to that particular temperature, with no admixture of products forming at other temperatures. Our knowledge of heat treatment is thereby increased, even though the exact procedure is not adaptable to commercial heat treatment of steels. Examples(2) of these T-T-T curves are given for a carbon steel (Fig. 1), for a chromium steel of moderate hardenability (Fig. 2), and for a composition similar to that under study in this work; having a high hardenability (Fig. 3).

Hardenability

Hardenability as a property of steel is no new thought. Understanding of the mechanism of hardening by heat treatment began with Jominy, Borgehold, Grossman, and many others(3). Certainly, by

* Formerly Metallurgist, Ross-Meehan Foundries, Chattanooga, Tennessee. Death came to Mr. Genung this fall shortly after he completed this article for the Journal of Steel Castings Research.

the efforts of these workers, commercial heat treating is now far removed from the taint of witchcraft and keeps company with the best of applied technology.

An invaluable tool in determining the hardenability of a given steel is the familiar End-Quench Test. This test results in a series of infinitely varying cooling rates from above the critical temperature.

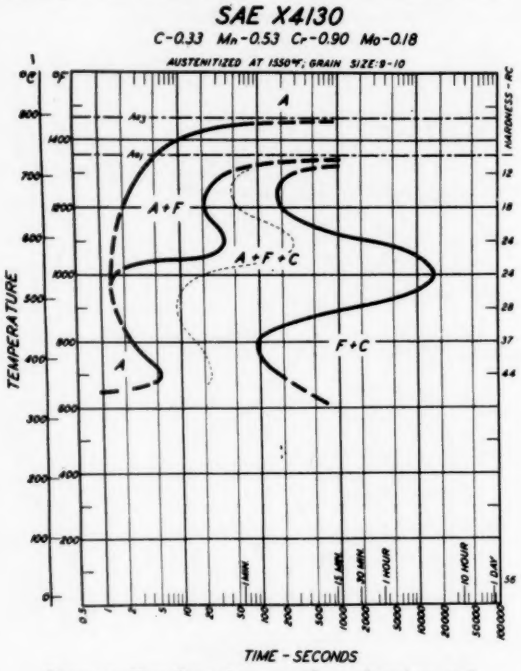


Figure 2—Transformation curve for a chromium steel

At one end there is a severe water quench and at the other end a rather slow air cool. Furthermore, the rates of cooling along the length of the bar are known quantitatively, so that the actual temperatures are at hand for any station along the bar, at any time after the beginning of the quench. By means of the test, the effect of any cooling rate on mechanical properties can be determined, and that information translated directly to operations. Not often are laboratory data so readily adapted or so easily understood.

These two laboratory procedures, the transformation or "S" curve and the hardenability curve, are concerned with the same problem, although this may not be readily apparent. The S curve has long been associated with structures developed at specific constant temperatures. The hardenability curve gives resultant hardness after a series of known cooling rates. Both concern microstructures and hardness after the establishment of a time-temperature relationship, simply because hardness, hence mechanical properties, is entirely dependent upon the microstructure.

Although a great deal is known about the cooling rates along the standard and quenched hardenability bar, under normal conditions little can be done to determine the microconstituents at the various stations. Several structures will exist in each field of view, each structure having developed as the bar cooled under the influence of the quench. And each structure is the result of the dwell within the temperature region at which it forms. The amount of each microconstituent, related to the whole, is dependent upon the rate of cooling and the transformation pattern of the steel. Therefore, the determination of the point on the bar where the austenite transforms to products other than martensite is difficult, if not impossible.

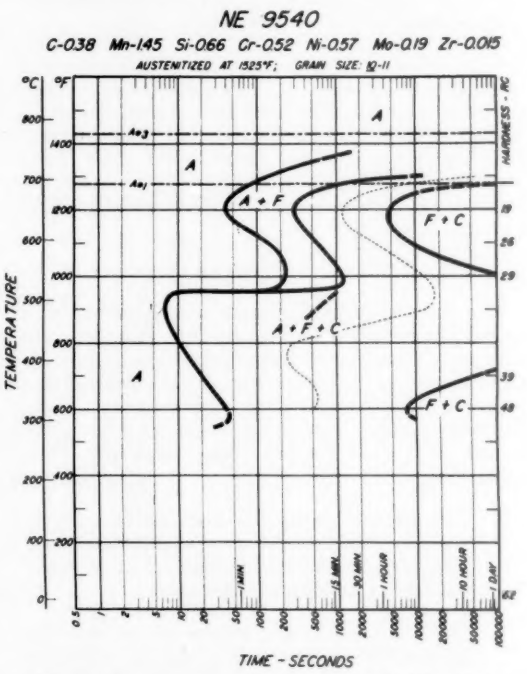


Figure 3—Transformation curve for a steel of high hardenability

C. A. Liedholm[4], however, has developed a technique for locating the beginning of transformation on cooling by metallographic methods. The results are fully as explicit as those obtained under isothermal conditions, and have the advantage of being directly translatable to commercial practice.

Essentially, the method consists of interrupting the usual end-quench test at the end of a certain predetermined series of times with a drastic overall quench. Obviously, the untransformed austenite remaining at any station on the bar at that time will become martensite in the overall quench, with any high temperature transformation product showing as a distinct structure against a background of white martensite. From the known data on cooling

rates at the stations on the end-quench bar and the times to the overall quench, construction of a time-temperature transformation curve under continuous cooling conditions is possible. The data obtained are precisely the same as that for the S curve, but are based on transformation during continuous cooling rather than at constant temperatures. This information, unlike the original "S" Curves, can be directly utilized in commercial heat treating processes.

Experimental Work

The experimental technique followed closely that of Liedholm. Standard one-inch diameter end-quench bars, of a heat of low-alloy cast steel of the composition shown in Table 1, were austenized at 1650 degrees F for 20 minutes after reaching temperature. At the end of that time, the bars were removed to the end-quench fixture and end quenched for periods varying from 5 seconds to 200 seconds. The normal end quench was interrupted by removing the bar from the fixture and quenching overall in a mixture of ice and water. The end quench times used in this work were 5, 10, 20, 40, 80, and 200 seconds, and are net, allowance being made for the time required to remove from the fixture and quench in ice water.

TABLE 1—Composition of Alloy Steel

	percent
Carbon	0.23
Manganese	1.11
Sulfur	0.028
Phosphorus	0.041
Silicon	0.47
Nickel	0.62
Chromium	0.52
Molybdenum	0.54

The usual longitudinal hardness traverse was made on each bar, after removing .015 inches on two faces, 180 degrees apart. The hardness values obtained were plotted against the distance from the quenched end for each item lapse to the overall quench. That distance from the quenched end to the point where hard martensite forms, other than that resulting from end quench, must indicate the existence of untransformed austenite at the time of the drastic quench. As the time in the quenching fixture increases, loss of heat through the effect of the end quench will bring the temperature into zones where high temperature transformation products are formed, indicated by hardness readings below those of the quenched end, or those of the full-hard martensite derived from the austenite untransformed.

Figure 4 shows the results of the hardness determinations on each of the several bars.

Microscopic examination along the length of the bar will show the exact point, measured from the quenched end, where these transformation products show against a background of white martensite. Identification of the structure is possible, but not necessary. The exact point on the bar where this product began to form from the austenite is what is wanted.

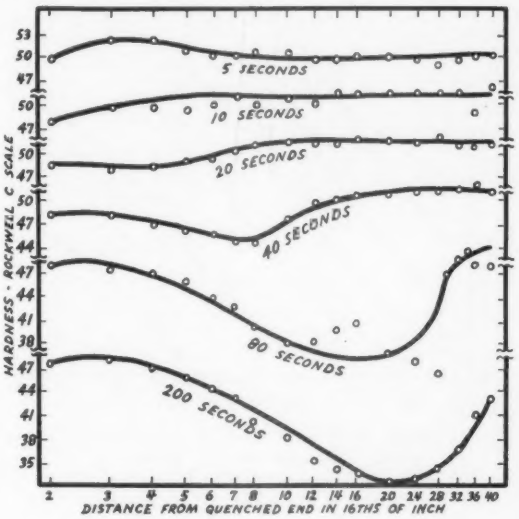


Figure 4—Hardness determinations on each of several bars

Results and Discussions

The data obtained from this study show that:

1. Under certain time-temperature conditions full hardness will result from a delayed quench.
2. The delay before the overall quench may be as long as 80 seconds under the conditions of the experiment.

It has been known for some time that full hardening would result if the cooling rate is such that the "chin" of the T-T-T curve is escaped. However, in actual practice such rapid cooling rates are often impossible due to the section involved, the alloying elements present and the ever-present hazard of heat treatment . . . susceptibility to quench cracks. The advantages of a delayed quench are obvious, then, to those charged with the responsibility of developing full hardness in commercial castings.

The results of the experiment in its present form are virtually useless. Cooling rates and resultant transformation temperatures must be established before any practical application can be made. Fortunately, many investigators, notably Boegehold and Liedholm [5, 6], have studied the cooling rates along the Jominy bar under the conditions of the standard

end quench. Fig. 5, taken from the work of the workers above, shows the time-temperature relationship at stations along the standard one-inch diameter end-quench bar. The chart is skeletonized to include only those items in the quenching fixture used in this work.

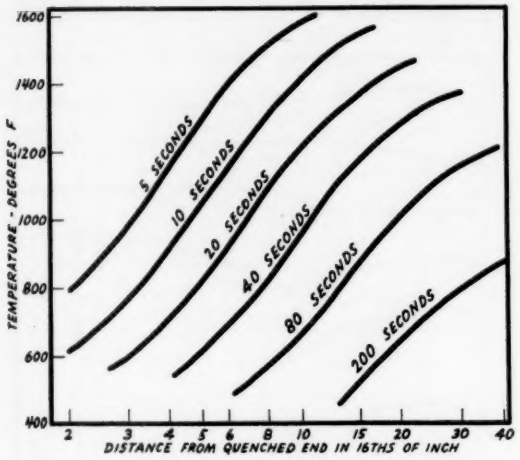


Figure 5—Temperature standard Jominy specimen after various quench times (*Boegehold and Weinman*)

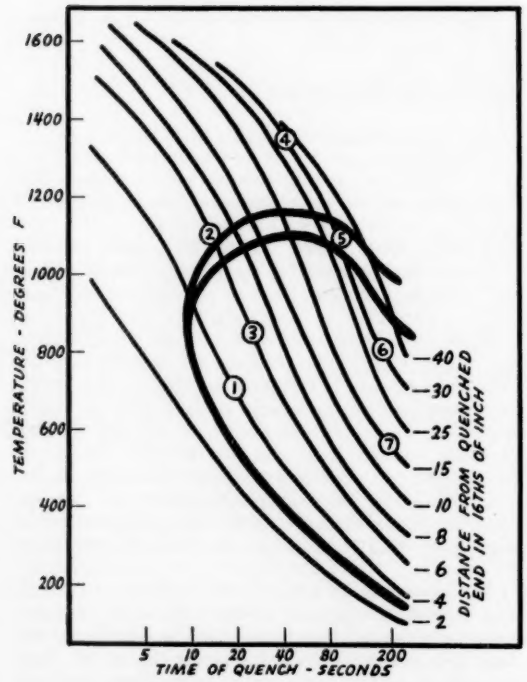


Figure 6—Transformation on continuous cooling of an alloy cast steel

Fig. 6 shows the same data as Fig. 5, with temperatures as the vertical axis, as in Fig. 5, but with the horizontal axis showing time after the beginning of the end quench. The distance from the quenched end is no longer pertinent, since Fig. 6 is essentially a family of curves representing several cooling rates. These cooling rates were derived from a standard end-quench bar, as a matter of convenience, but results obtained may be translated directly to parts of other geometry.

The feature of greatest concern now is the point on each of this family of cooling curves at which the initial austenite transforms to other products. In the discussion of the hardnesses of Fig. 4, a high hardness value, other than that found at the quenched end, would indicate the existence of untransformed austenite at the time of the overall quench. If the distance from the quenched end to this point of regained hardness is set against the time in the quench fixture, the data of Table 2 result.

TABLE 2—End-quench Distance to Full Hardening

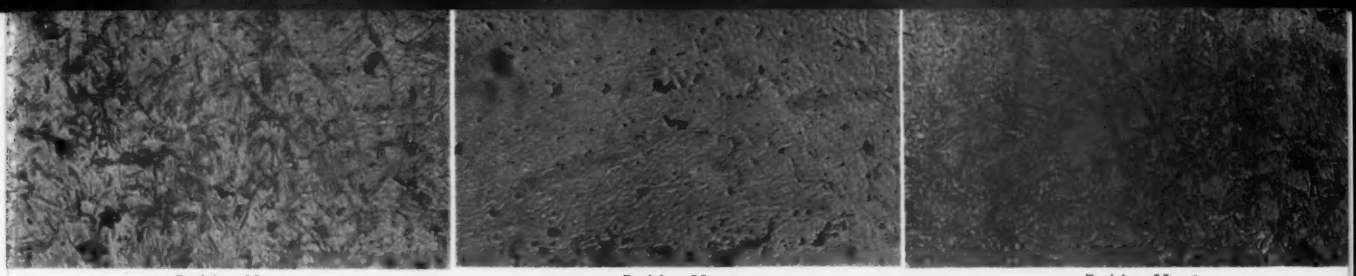
Time of End Quench	Distance Sixteenths
5	Fully Hardened
10	Fully Hardened
20	8
40	14
80	34
200	More than 40

Using this distance and the time elapsed from the beginning of the end quench to the overall quench, on Fig. 6, the temperature, at which transformation began, may be located.

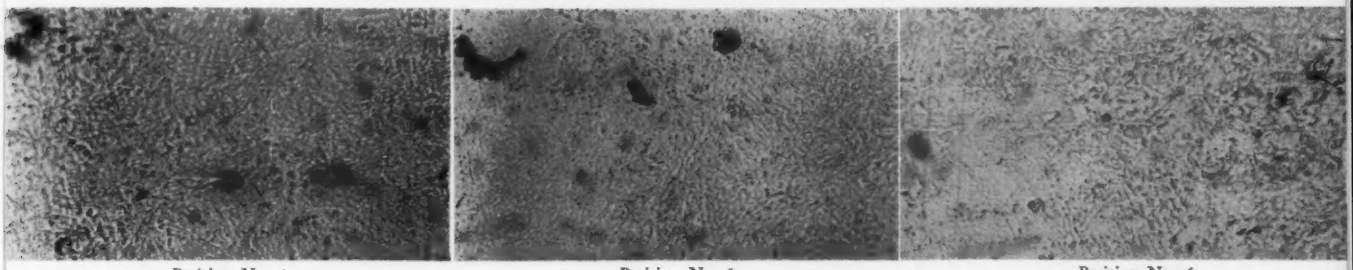
This temperature is represented in Fig. 6 by the heavy black line. The area enclosed by this "loop" is a mixture of ferrite, bainite, and martensite, the quantity of each constituent varying with the cooling rate. The area outside the transformation loop is austenite or martensite depending on the temperature.

The position of this beginning transformation line is indeterminate for time lapses of 5, 10, and 200 seconds. Since the 5 and 10 second bars are fully hardened throughout their length, the nose of the transformation curve must be to the right of the 10 second line. Reference to Fig. 4 will show that, given time enough, hardness values on the quenched end will begin to fade away at four-sixteenths. Therefore, the left boundary of the transformation line in Fig. 6 must be between the two and four-sixteenths line.

Inasmuch as transformation persists throughout the length of the 200 second bar, the transformation line must take the course shown in Fig. 6, i.e., open on the right side.



Position No. 1 Position No. 2 Position No. 3



Position No. 4 Position No. 5 Position No. 6

Figure 7—Typical microstructures which locate transformations in Figure 6

Fig. 7 shows certain typical microstructures which more precisely establish the location of the line of transformation and, in addition, indicate the areas in which free ferrite separates prior to the beginning of the bainite transformation. Each micrograph is keyed in Fig. 6 to the location from which the specimen was taken. Thus, by means of hardness readings and micrographs, the temperature at which austenite begins to transform to another structure, is located.

Above the heavy transformation line, full martensite will result from a quench, even though the temperature may have fallen to about 1200 degrees F before the quench. Points to the left indicate rates of cooling exceeding the critical cooling rate, comparable in practice to a normal quenching process. Hence the chin of the S curve has been escaped. Points above show the results of the action of the quench on untransformed austenite at temperatures between the nose and chin of the S curve, predicting the success, in theory at least, of a delayed quench.

From the results of these tests, it must be concluded that comparatively slow cooling rates, similar to those of an air cool, prior to the quench will be far better insofar as full hardness is concerned. And a quench designed to exceed the critical cooling rate may not be wholly successful, particularly with moderate-to-heavy metal sections.

There are two explanations offered for this. First, with a quench of given effectiveness, success is more likely with the delayed quench, since the temperature must drop only from 1200 degrees F (the temperature at the beginning of the quench) to the bainite chin at 900 degrees F within an allowed 10 seconds. For obvious reasons, the direct quench from 1650 to 900 degrees F within 10 seconds is far less likely to succeed. Secondly, a quench from a temperature near 1200 degrees F is much more effective. Fig. 8 is a diagrammatic illustration of the cooling rates at the surface of a small cylinder in an agitated water quench. It is seen here that the quench effectiveness is poor until the temperature has fallen to about 1200 degrees F. It is reasoned that a vapor blanket surrounds the work to be quenched during the early stages of the quench, which prevents contact of the liquid with the work. When this vapor blanket no longer persists, then the cooling power of the agitated liquid medium becomes fully effective.

It is certain that the position of the line of transformation in Fig. 6 is the result of the operation of both of these factors involved in the quench. This, of course, detracts nothing from the usefulness of the knowledge gained. The important feature here is the knowledge that the water quench may be delayed until Ae_1 is approached, with a more effective quench resulting from the lowered temperature at the time of the quench.

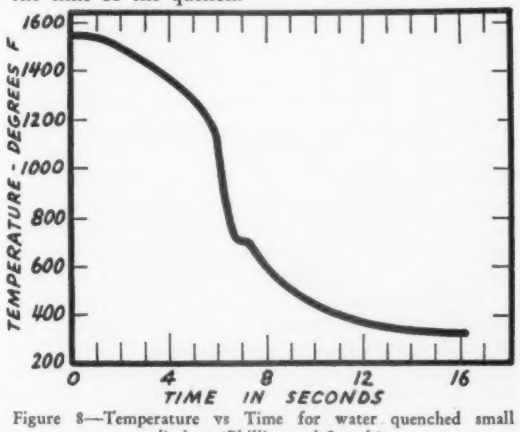


Figure 8—Temperature vs Time for water quenched small cylinders (Phillips and Lynch)

With all the emphasis on full-hardening and martensite, it is well to recall that a tempered martensitic structure results in maximum mechanical properties, particularly those relating to shock loads or resistance to fatigue. Examination of structures

(continued on page 7)

QUALITY IMPROVEMENT PROGRAM
SAND EVALUATION TEST BLOCK

*George Di Sylvestro**

The sand evaluation test block used in SFSA Research Report No. 33 (Fig. 1) has been used as far back as 1945 by the Naval Research Laboratory by Messrs. R. E. Morey and J. R. Kattus, "Preventing Veining and Penetration on Castings made in Synthetic Sands" Trans. AFS Vol. 54, 1946, page 129. This design also has been referred to in the progress report of the Standard Test Patterns Committee 8-T by Charles Locke, "Current Status of Test Patterns for Evaluation of Sand Mixtures" 1955 AFS Preprint 55-111.

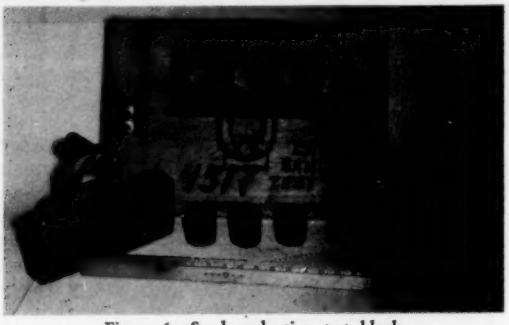


Figure 1—Sand evaluation test block

Burnside Steel Foundry Company has made many castings using the sand evaluation test block design and has found that it is adequate for evaluation of casting surface finish. However, in interpreting these results some consideration should be given to the position of the ingates since these ingates constitute a variable which must be considered. This fact became evident in some studies that were made by Burnside Steel Foundry Company on an investigation of raw materials. It was found that even though the three core inserts were the same in every particular they did not produce the same surface finish in the casting. The two end specimens usually will produce comparable surfaces but the center specimen often results in producing a poorer surface.

The reason for this variability in the test is probably the location of the end gates producing a condition of hot metal flowing around the center specimen. This suggestion is a reasonable one for it has been observed, from test blocks that have cooled to room temperature, that the center areas of the outside sand specimens have not had the binder burned out whereas the center specimen, which has been subjected to the highest temperature, has burned out the binder completely. This condition may be observed by the discoloration in the two end sand specimens of the evaluation block in Fig. 2.

The casting surfaces produced after the cores have been removed are shown in Fig. 3. It can be seen from this illustration that the surface of the center cored area is considerably rougher than either of the end cored areas even though all three cores or sand specimens were identical.

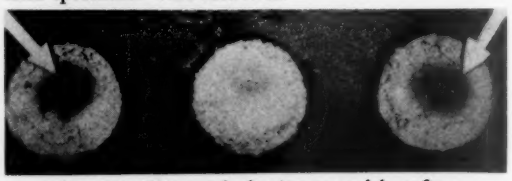


Figure 2—Photograph showing unequal heat flow

Figure 3—Surface condition of the test shown in Figure 2

These results mean that either the center sand specimen should not be evaluated, or it should be deleted from the block, or a new test block or a different method of gating should be designed.

The latter course was taken at Burnside Steel Foundry Company and Fig. 4 is a sketch of the suggested test block design. It is a 1-inch thick by

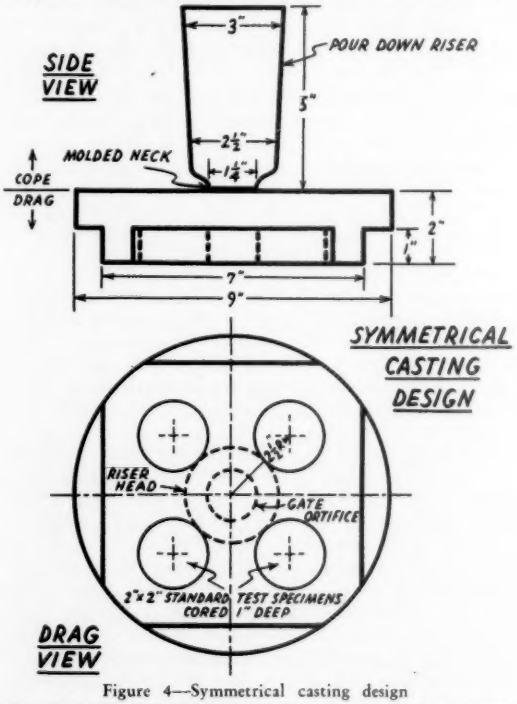


Figure 4—Symmetrical casting design

* Sand Department, Burnside Steel Foundry Company.

Figure 5—Symmetrical casting pattern equipment

9-inch diameter plate on top of a 1-inch thick by 7-inch square plate with four 2 by 2 inch standard specimen cores placed equi-distant from the center. It has a 3-inch diameter necked down green sand gate riser which is centrally located. A splash core at the bottom of the gate-riser can be used to eliminate erosion in case the sand is weak. The pattern equipment and test castings are illustrated in Fig. 5.

This sand evaluation test block has been used extensively at Burnside in evaluating the importance of pH values, refractory additives, sands, bentonite, and veining. Uniformity of casting surfaces can be seen in Fig. 6 when four identical sand specimens were used.

Further studies on veining, when using this test block design, have shown that if the sand specimen produced a reentrant angle the sensitivity of the formation of veining would be improved.

Tests have shown the effects of silica flour additions on casting surface finish with consistent duplication of casting surface finish with consistent duplication of casting surface conditions. Fig. 7 shows the mold cooled to room temperature and examined before blasting. It will be observed that as the silica flour content increases in the core the discoloration increases; or, in other words, the heat conductivity of the sand decreases.

Four sand mixtures can be evaluated simultaneously with the modified design of sand evaluation test castings. The pouring weight is 35 pounds.

Figure 6—Uniform testing conditions in the symmetrical casting design

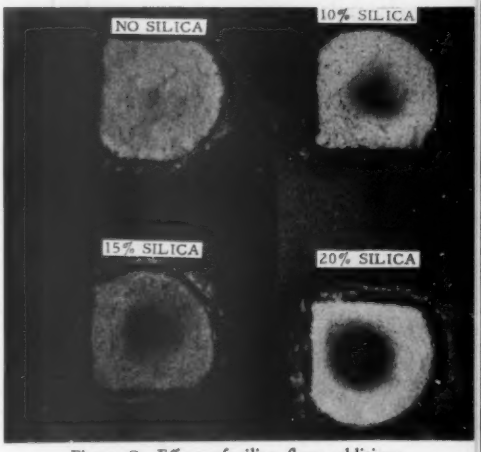


Figure 7—Effect of silica flour additions

Transformation While Cooling (continued from page 5)

other than martensite, resulting from transformation at high and intermediate temperatures shows a coarse heterogeneity, composed of weak ferrite intermixed with stronger carbide. This type of structure must result in a complex susceptibility to early failure under the conditions given above. Treatments which result in admixtures of pearlite or bainite with tempered martensite will not develop the full capabilities of the material.

It is this last, the pointing out of the mechanics of quenching for full hardening, that is the useful result of this work.

The theoretical approach given above has been checked repeatedly under actual plant conditions and the results obtained show very close agreement between theory and practice. Hardness, tensile properties, and V-notch impact fall within narrower limits than before, when the procedure was such that the quench could begin at temperatures no lower than 1550 degrees F. The practical advantages of the new method are obvious.

Credit for the work reported herein is given to the metallurgical staff of Ross-Meehan Foundries, and to the management for permission to publish the results. Much credit, too, must be given to those workers cited in the text who have attacked the same problems, and have contributed so ably to the fund of knowledge of the heat treating process.

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RESEARCH PROGRAM

PROGRESS REPORT ON ACTIVE PROJECTS

Research Project No. 19
Studies of Design Factors As Related to Methods Of Manufacture

Strength of material text books and literature supply the designer and engineer with formulae and procedures by which theoretical sizes and dimensions of various shapes and sections may be determined to suit certain load, stress and operating conditions. The theoretical results are generally modified by the introduction of a so-called "factor of safety" which varies, depending upon the material, how it is used, service requirements and many other factors.

The so-called "factors of safety" applicable to steel structure have been largely a matter of the judgment and experience of engineers. Engineers have long been aware of the need for a better understanding of the "factors of safety" and limiting stresses as they may be influenced by methods of manufacture and fabrication of structural elements and machine.

Many individuals in the steel casting industry have long recognized that steel castings are all too commonly over-designed and are subject to unnecessarily rigorous customer inspection largely because of a lack of confidence as to what steel casting sections will bear in service.

The Technical Research Committee recognized the need for fundamental design factor data. As a result a research program of gathering basic experimental data on the response of cast steel and weldment sections to loads and stresses imposed by fatigue service is being conducted at Case Institute of Technology.

The original program called for two styles of design, a box section, B, and "L" section, A. Various modifications of these two design styles were proposed by employing different designs at the corner junctions. The individual casting or weldment is sectioned to obtain individual specimens.

The specimen can be described as being two rectangular bars (⅝ x 1 inch) connected together at right angles in a convenient joint. The principal difference between the casting specimens is in the selection of the inside and outside fillet radii at the knee. Four corner designs were proposed. The dimensions at the knee were as follows:

Type 1— ⅛" outside and ⅝" inside fillet radius
Type 2— ⅝" outside and ⅝" inside fillet radius
Type 3—1¼" outside and ⅝" inside fillet radius
Type 4— ⅞" outside and ¼" inside fillet radius

The weldment specimen types differ mainly in the method of welding the rectangular bars into the two styles of design. Four methods of fabricating the corners were recommended. The corner designs are illustrated in Figures 1 and 2, for both the casting and weldments.

The Technical Research Committee felt a preliminary study was in order before purchasing all the castings and weldments needed for the study as it was their opinion that certain weldments were not suitable for fatigue studies.

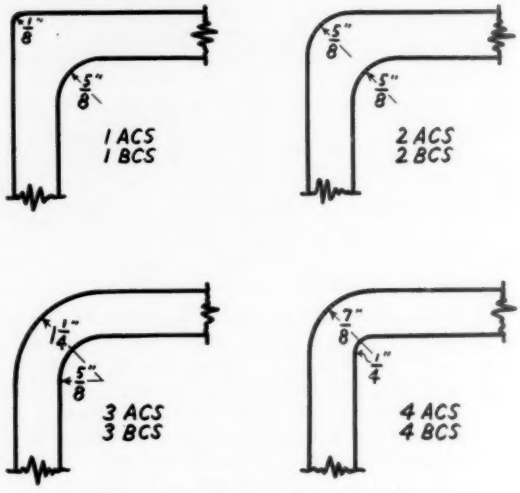


Figure 1—Corner types for steel castings

For the preliminary study the weldments were furnished by The Falk Corporation and the castings were furnished by Dodge Steel Company.

The chief purpose of the preliminary study was to determine if certain proposed designs should be eliminated in the final program.

The Preliminary Study

The preliminary studies revealed that the fatigue life of cast and welded plain carbon steel shapes must be considered as the net results of the interrelation of four major variables which ordinarily affect the fatigue life of materials. The variables are:

(1) dimensional and geometric variations between specimens of the same type;

(2) surface conditions unique to each individual specimen;

(3) inherent material defects or microresidual stresses in critically located unit particles of the material;

(4) stress concentration.

A summary of the test data is found in Table I.

Photoelastic Studies

Photoelastic analysis showed that the center of the fillet was the region of stress concentration for specimen Types 3 ACS and 4 ACS. Photoelastic analysis also showed that the stress concentration of the Type 4 ACS and the 1 AW specimens was localized about the center of the inside at the knee, and that the stress concentration of the Types 2 ACS, 3 AW and 4 AW was in a region very close to the point of tangency between the rectangular arms of the specimen and the inside fillet of the knee.

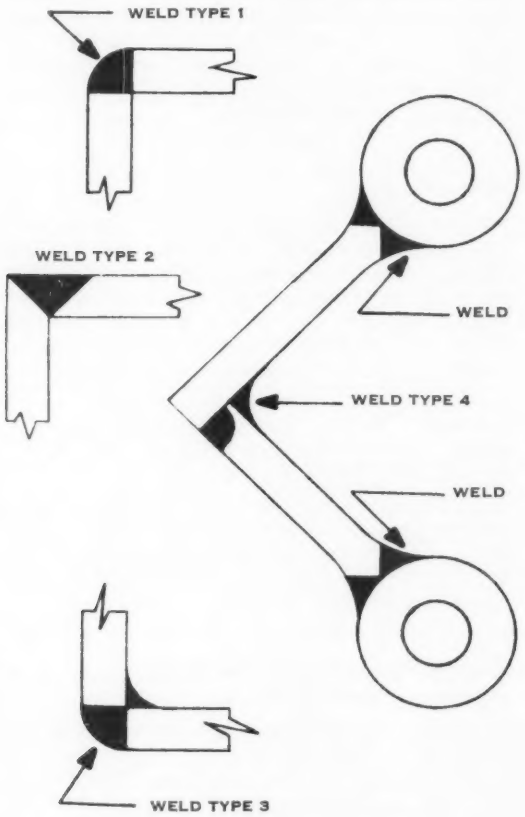


Figure 2—Corner types for steel weldments

An examination of the photoelastic studies made of the Types 1 ACS and 2 ACS cast steel specimens showed that the corner and outside fillet of these designs are not seriously stressed. Therefore, surface irregularities in this region such as grinding scratches do not seriously affect the fatigue life of the specimen.

Conclusions of the Prelimary Study of the "L" Design (A)

Because of the comparatively few specimens tested for each type, the conclusions presented with this report can best be evaluated as a trend that still requires statistical verification.

1. There is some doubt about the design criterion of rounding out the outside corner of joining sections with a radius selected to make the section equal to or less than the thickness of the joined members. The advantage gained by the increase in soundness at the joint by the reduction of centerline shrinkage might not be as great as the disadvantages acquired by increase stress concentration, especially when the ratio of inside fillet to joined section thickness is equal or less than 0.4.

2. The successful performance of a cast or fabricated member that is known to be affected by fluctuating stresses depends upon the cooperation between designer, pattern maker, and molder in the one instance, and between designer and welder in the other. Each should attempt to maintain nominal dimensions, to strive for a superior surface, and to strive for sections free from discontinuities in regions known to be affected by stress concentrations.

3. The cast steel specimens show an average fatigue life of about 6 times greater than those of similar geometry of the welded shapes.

4. It is very probable that cast steel shapes respond more readily to improved design than their equivalent counterpart in welded shapes. The versatility of shape possible with cast steel should be exploited with other geometric

TABLE 1—Summary of Test Data*

Specimen	Range in Fatigue Cycles	Average Cycles	Range in Nominal Stress Fracture	Average Stress
4 ACS (Casting)	5,000- 12,000	9,000	68,000-84,000	76,000
2 ACS (Casting)	7,000-747,000	380,000	44,000-67,000	55,000
1 AW (Weldment)	5,000- 15,000	8,000	58,000-68,000	62,000
3 AW (Weldment)	26,000- 80,000	47,000	45,000-47,000	46,000
4 AW (Weldment)	24,000-125,000	45,000	49,000-59,000	54,000

* All testing performed with 650 pounds static preload, 650 pounds dynamic load.

configuration in which the legs are tapered down from the joint towards the bearing-pin holes (resulting in a "constant stress" effect on the specimen which would also reduce the stress gradient at the joint) might offer an improvement in fatigue life not readily attainable by the "L" junction design used in casting and welding fabrication.

Fatigue Studies of the Type B Specimen Design; the Closed Box Frame

The preliminary studies of the Style B design were limited to type 1 corner for the casting and type 3 corner for the weldments. The weldments were tested under two conditions: as welded and fully annealed.

The specimens were tested by applying a single load, 3500 pounds static tension preload, 3500 pounds dynamic preload on a Sontag testing machine to study design and strength characteristics of the specimens by their response to fatigue life. Each gross casting was sectioned into 10 specimens and each weldment into 12 specimens.

I. Cast Steel Specimen, Type 1-BCS
   - A. Spread of fatigue life from 70,000 to 586,000 cycles
   - B. Average fatigue life at maximum load: 187,000 cycles
   - C. Average nominal fatigue stress: 57,500 psi

II. Welded Steel Specimens, Type 3-BW
   - A. Welded Type 3-BW (annealed)
     1. spread of 40,000 to 70,000 cycles
     2. average life, 52,000 cycles
     3. average nominal fatigue stress 42,900 psi
   - B. Welded Type 3-BW (as welded)
     1. spread of 53,000 to 86,000 cycles
     2. average life, 69,000 cycles
     3. average nominal fatigue stress, 43,900 psi

Summary of Results for Style B Specimens

1. The average fatigue life of the Type 1-BCS cast steel specimens was found to be about 2.7 times greater than the best performance of the welded Type 3-BW specimens. The average nominal stress at the fatigue fracture was observed to be about 57,500 psi for the cast steel specimens and about 43,900 psi for the welded specimens.

2. Cast steel specimens showed a definite trend to superior fatigue life when sectioned from the top or bottom portions of the gross castings.

3. During the static tension tests, the cast steel specimens were observed to undergo a greater degree of deformation than the welded specimens before fracture.

4. It is the thought that the self-quenching of the first few welding passes in the assembly of the weldments and the tempering that occurred with subsequent welding passes might have been instrumental in effecting a slight but noticeable improvement of the performance of the as-welded specimens over that of the annealed. In the light of the work done by several investigators who found considerable improvement in fatigue life of high carbon and alloy steels with heat treatment, it can be speculated that a normalizing heat treatment rather than annealing could make a better contribution to the fatigue life of steel castings.

Future Program

After the data had been reviewed by the Technical Research Committee, it was decided that the complete program should include only the type 3 and 4 corner designs for the two style weldment designs, and for the two style casting designs; corner types 1 and 2 should be studied fully and corner types 3 and 4 should be studied partially.

Accordingly, 33 weldments were secured from the Automatic Welding Company and the necessary castings were ordered from American Steel Foundries and Dodge Steel Company.

Each gross weldment was sectioned into 13 specimens and each casting was sectioned into 5 specimens. The work of the final program was started in February of 1955 and the testing should be completed by the summer of 1956.

Progress Report on the Box Frame Weldments, Types 3-BW and 4-BW

Sufficient data on the Closed Box Frame Weldments Types 3-BW and 4-BW are available for a few observations, but no comparison can be made with the cast steel specimens.

All welded specimens were originally loaded with 3500 pounds static tension preload and 3500 pounds dynamic load. This resulted in a load cycle varying from zero to 7000 pounds at the rate of 1800 cycles per minute.

It was observed under this condition of testing that the welded specimens failed in the range of 40,000 to 60,000 cycles. The Technical Research Committee felt the number of cycles was too low to be significant. Therefore, the preload was reduced so that failure occurred in the range of 100,000 to 300,000 cycles. It was found that a 2500 pound static tension preload and 2500 pound dynamic load resulted in the desired range in fatigue life cycles.

Type 3-BW Welded Specimen

The fatigue failure for the type 3-BW always occurred at the junction of the inside fillet weld and the specimen leg as shown in Fig. 3. The first sign of a fatigue crack appeared at some random spot along the line of the surface interface. The tiny crack would propogate laterally in both directions until the sides of the specimen were reached. The fatigue crack then progressed through the specimen. The rate of propogation of the fatigue crack was not consistent. For example, the number of fatigue cycles after the first appearance of the crack varied from 70,000 to 150,000 cycles when the total preload was 5,000 pounds.

The hand-welded 3-BW series did not seem to indicate any real significant difference in both nominal failure stress and fatigue life when tested as-welded or stress relieved at 1100 degrees F.

The data for the 3-BW series that were fabricated by the submerged arc process, indicate there is no significant difference between the as-welded and stress-relieved specimens at the high load (7000 pounds), but there is some improvement in the fatigue life of the as-welded specimens at the lower load (5000 pounds). The failure of such evident improvement in fatigue life between the as-welded and the stress-relieved specimens in every instance, rather than several instances, suggests that the effect of heat treatment should not be considered the single major reason.

The endurance limit of the submerged-arc-welded specimen begins to show up at a nominal stress of about 16,000 psi, and for the hand-welded specimens at about 18,000 psi. It is very probable that some specimens could go on to infinite life at a higher stress in both the hand-welded and submerged-arc-welded specimens and, likewise, some specimens could fail at even a lower stress.

Type 4-BW Welded Specimen

Two distinct types of fatigue failures were observed to be typical of this specimen design. The most frequent fatigue failure, which is called the Type I failure, as shown in Fig. 4, was observed to

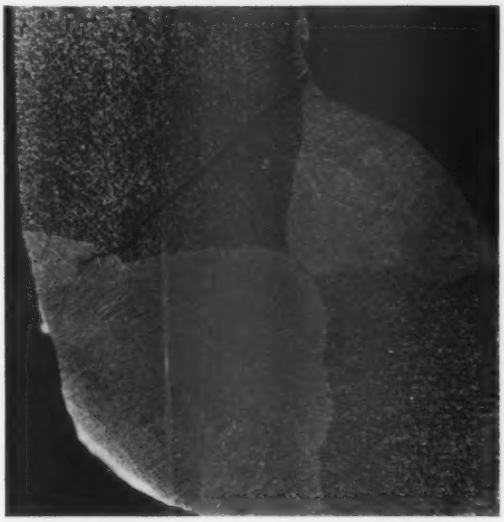


Figure 3—Fatigue crack characteristic of Type 3-BW Weldment

start in the region of the junction of the inside fillet weld and the specimen side and to progress into the U-groove butt weld. In the Type II fatigue failure, which is shown in Fig. 5, the fatigue crack was observed to start at the junction of the fillet weld and specimen leg and to progress through the section of base metal.

The data indicate that where the Type II fatigue failures were predominant in the weldment, the fatigue life of the specimens, considered collectively, was appreciably superior to the fatigue life of specimens where the Type I failure was predominant.

The data on the component part type of test specimen, 4BW, seem to indicate that the weld is not necessarily stronger than the base metal but that the weld was stronger than the heat-affected zone. Also, that the build-up of excess weld metal at the top of the U-groove butt weld could be instrumental in improving the fatigue life of component parts that are affected by stress concentration in other regions. Of course, this implies that there

Figure 4—Type I Fatigue Failure for 4-BW design

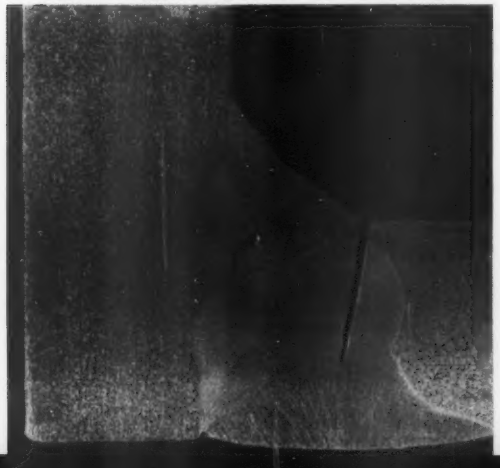
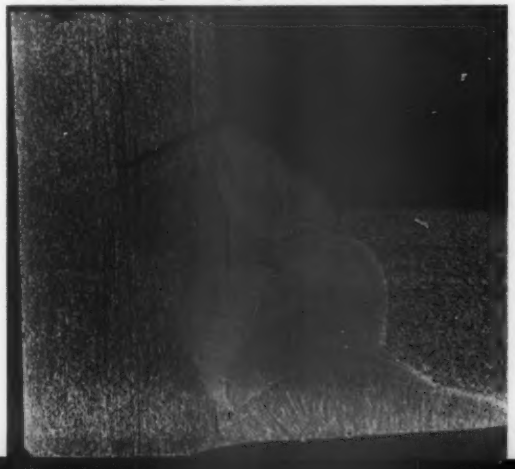


Figure 5—Type II Fatigue Failure for 3-BW design



are no abnormal concentrations of stress in the build-up area.

The data to date seems to justify the following conclusions:

(1) There is no real significant difference between the hand-welded and submerged-arc processes in producing a superior or more uniform specimen. The as-welded state showed better fatigue life in both the hand-welded and the submerged-arc-welded specimens of the Type 3-BW specimen design; however, stress relieving the 4-BW specimens fabricated by the submerged-arc process at 1100 degrees F. showed a fatigue life of the same order as the as-welded specimens. Therefore, it appears that the state of heat treatment for weldments should be considered as playing a minor part in fatigue life and the resistance to fatigue can be attributed to other causes.

(2) The excess weld metal need not always be avoided or ground off as though it was detrimental to fatigue life of a component part. In fact, it can be instrumental in improving the fatigue life.

(3) Stress concentrations and the incipient fatigue crack always occurred at the interface of the fillet weld and the specimen.

Research Project No. 25 Fatigue Properties of Comparable Cost and Wrought Steels

Research Report No. 35 covering an investigation of the fatigue properties of carbon and low-alloy cast steels, as well as a number of comparable wrought steels, was sent to the member companies during October 1955. The regular printed edition was soon exhausted inasmuch as the member companies requested additional copies of the report for their sales staffs as well as for their technical and operating staffs. The second printing has been made and therefore there are sufficient copies, at 75 cents each, to fill orders for member companies.

It is hoped that the report will be published and presented in a somewhat condensed form by American Society for Testing Materials at the Annual Meeting of that Society during June 1956.

NEW PROJECTS ON SAND

Research Project No. 43 Inorganic Bonding of Molding Materials

Two new research projects (43 and 44) have been formulated recently by the Technical Research Committee and the appropriations requested have been approved by the Board of Directors, SFSA. These projects refer to the binding of sands and other possible molding materials that can be used in the steel foundry.

Objective of the Research . . . The objective of the research is to study the properties and behaviors of potential inorganic bonds, other than clay, and to develop materials and processes suitable for the bonding of molding materials for the production of steel castings.

Scope . . . Molds for steel castings usually consist of silica sand bonded together with clay, organic materials and water. In some cases, as in the shell molding process, the bond is merely an organic material.

Large quantities of gas are generated when molten metal comes in contact with organic bonds. This gas has been observed to bubble through the metal in the research study on the flow of metal in gates and often brings with it particles of the mold surface. The gas produces pit-type defects in shell molded castings and is responsible for misrunning of the mold in some cases.

It has been suggested that high quality aircraft castings can be produced only in molds of very low gas formation.

Mold and core properties that are desired through the use of inorganic bonds, other than clays, are: (1) a hard, accurate mold should be produced; (2) it should be an effective bond at molten steel temperatures up to 3150 degrees F; (3) it should permit molds to be cured quickly; (4) molds bonded with an inorganic bond should become pyroplastic and lose brittleness at high temperatures, but retain shape; (5) such molds, however, must easily disintegrate after being cast; (6) the mold and binder should be free from gas; (7) the mold and associated bond should be inert toward the molten steel and cause no pickup by the metal of contaminants from the mold; (8) the binder should be readily available, economical, and be of such a nature as to permit ready fabrication of a mold at room temperature either by ramming, slurry molding, or blowing.

Research Procedure . . . Inorganic bonding materials fall into the following categories: (a) soluble silicates; (b) inorganic gells or concentrated dispersed-phase systems: (c) hydraulic cements; (d) borates, and (e) phosphates. Materials of all of these types will be investigated to establish the best compositions and processing methods for inorganic binders in each class.

Further detailed investigations then can be directed toward the development of producing the molds and

pouring them with molten steel and evaluating their possibilities.

A systematic investigation will be made of known materials. These materials and the conditions necessary for the control of the various reactions will be selected, and bonded sand specimens will be prepared. Information will be sought on: (1) setting time; (2) green strength; (3) baking conditions; (4) baked properties; (5) thermal shock resistance; (6) properties at high temperatures; (7) dimension and size stability during curing, baking and subsequent heating or use; (8) gas evolution; (9) reactivity with molten steel, and (10) mold erosion.

Experimental bonds which prove of interest after the above tests would be selected and detailed investigations of mold making techniques conducted. Molds would also be constructed and evaluated in the laboratory before they are recommended for foundry trial. Acceptable experimental bonds would be used in the foundry to produce various size castings.

Research Agency . . . Horizons, Inc., a Cleveland and Princeton, New Jersey, organization, specialists in research and development in the fields of metallic and non-metallic materials, has been selected by the Technical Research Committee to execute the program of research. Laboratory and experimental facilities required to execute the program are available.

Estimate of Time and Cost of Research . . . . It is estimated that it will take approximately three years to complete the studies of this research program. The costs are estimated to be about $100,000 for the three-year period.

Research Project No. 44
An Investigation of Close Packing of Sand and Development of Effective Clay Bonds

Objective of the Research . . . The research is designed to improve the surface of steel castings through the elimination of included mold materials. To accomplish this, basic knowledge of sand grain distributions and effective bonds must be secured.

Scope . . . Sands, refractories and binders are extremely important raw materials for making steel castings; not only do they represent huge expenditures, but defective castings resulting from their improper use are costly.

Far too little is known about these raw materials and their potentialities in spite of many years' experience in their use. The relatively low cost and availability of sands and clays will, in all probability, determine that these materials will be the basic tonnage ingredients for steel molding use for many years to come; this, in spite of recent developments of interesting and potentially applicable organic and inorganic binders and ceramic type molds.

Steel castings are plagued today with surface defects which result from molding material lodging in the casting surface. These defects produce magnetic particle indications with subsequent exploration and repair. Sand inclusions in the casting skin also increase machining costs and are troublesome.

It is believed that surface inclusions of molding materials do not have to be a consequence in producing steel castings. Preliminary studies have indicated that control of sand grain packing and efficient clay bonds will produce some sands that have toughness and plasticity, and stand up under sudden heat shock. They are not brittle, and erode and scab easily.

At present such desired sands are produced only occasionally because the fundamentals leading to their production are not fully known; and the little that is known requires further exploration and development to translate the information into practical application.

Research Procedure . . . The program of research will cover two phases: (1) clays, and (2) sands.

Clays

1—Collate and interpret for steel foundrymen, the data that exists on the chemistry, crystallography and nature of various classes of clays used for steel molding.

2—Experimentation to find ion exchange reactions which would improve bonding characteristics and increase strength of sand-clay mixtures.

3—Studies of methods of uniform coating of grains with bonds of various thicknesses and determination of sand toughness.

4—Study the drying-out tendencies of bentonite clays, and reduce or eliminate this tendency.

5—Examine the variability of performance of bentonite and develop purchase specifications.

Sand

1—Study inter-particle friction of sands, under compression and lateral movement against pattern surfaces, and determine its effect on packing density.

2—Research on producing maximum packing of sand grains with minimum binder at the mold-metal interface.

3—Studies on the distribution of sand grains, the blending of sands and their toughness properties.

(continued on page 15)

INFLUENCE OF THE METALLURGICAL PROPERTIES OF CAST STEELS ON THE TENDENCY TO HOT TEAR

Steel foundrymen have carefully followed research and developments on causes and cures of hot tears and the Society has published summaries of hot tear information as it has become available. The following is an abstract of an article by H. Heyer and E. Piwowarsky published in German in the trade magazine "Giesserei" Vol. 42, 1955.

The factors responsible for the incidence of hot tears can be separated into two classes: (1) those concerned with the metallurgical properties of the cast steel and (2) external factors. One comprises the composition, the gas content, the degree of segregation, and also the solidification range of the steel.

This review of the study conducted by Heyer and Piwowarsky is concerned with the metallurgical variables which contribute to the incidence of hot tearing.

Experimental Study

An experimental, straight cylindrical specimen was employed so as to minimize the effect of the external factors as much as possible. In this way the external conditions could be kept fairly constant and the non-uniformities of contraction and solidification could also be kept to a minimum.

The specimen was 13.4 inches overall in length as shown in Fig. 1. At the approximate mid point an abrupt section change from ¾ to 1 inch was designed into the test specimen. The specimen is

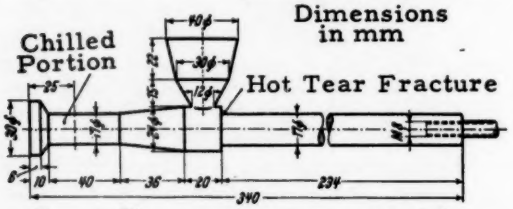


Figure 1—Hot tear specimen (1 mm = 0.04 inches)

risered with the contact point one-quarter of an inch from the change in section. The heavier section side was tapered down to the diameter of the lighter section and was chilled at the end by a plate.

The end plate of the heavier section contains a steel insert. The lighter section end of the specimen contains a ⅜ inch threaded bolt which is centered and extends ¼ of an inch into the specimen. The chilled ends act as restraints to normal contraction of the cast specimen. The threaded bolt is connected through a cooling system to a spring system. Solidification of the specimen is directed by the chilling action of the end plate and the bolt inserts towards the center junction. The hottest zone during cooling is near the riser and because of the sharp change of section, a hot tear fracture will occur in this area.

As the casting solidifies the shrinkage is opposed by a spring force. The expansion of the spring is measured in thousandths of a millimeter. A certain deflection of the spring at a definite temperature will cause hot tearing at the junction of the cylindrical sections.

Experimental Results

The spring expansion values obtained reflect the hot tearing resistance of a particular specimen. The greater the spring deflection the greater the hot tearing resistance. The values are specific for the test conditions and the interpretation enables only generalized statements to be made.

About 160 specimens were cast from steel produced in an acid-lined induction furnace. The springs were chosen so that properly made steel under favorable pouring temperatures resulted in solidified specimens without hot tears.

Carbon Content

The effect of carbon was determined on simple carbon steels containing 0.06 to 0.70 percent carbon. These steels were poured at 190 degrees F above the liquidus to maintain constant pouring conditions. Fig. 2 shows the results of this study.

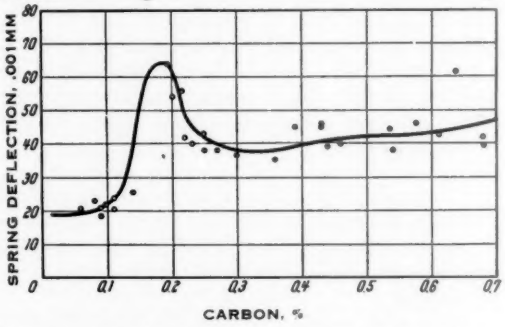


Figure 2—The effect of carbon on the hot tearing resistance of cast carbon steels

As can be seen from Fig. 2, the greatest hot tear resistance occurs at 0.20 percent carbon. This is a very interesting point as the hot tearing resistance shown in Fig. 2, measured in spring deflection, is contrary to the belief of other researchers in this field.

Rassenfoss states that 0.25 percent carbon is the most susceptible to hot tearing and an increase from 0.17 to 0.25 carbon is accompanied by a decrease in hot tear resistance. Wyman, studying a narrower range from 0.19 to 0.25 percent carbon, states that there is an increase in hot tears when going from 0.19 to 0.25 percent carbon. Middleton and Protheroe say that as the carbon content is increased above 0.15 percent carbon the steels' resistance to hot tearing is reduced.

Commercial cast steels produced in the basic open-hearth also showed the maximum hot tear resistance to be at 0.20 percent carbon in the German study. The authors have explained the high resistance of 0.18 percent carbon on the basis of the short solidification time. An examination of the iron carbon phase diagram shows this point at the peritectic composition. The peritectic composition attains its hot strength more rapidly than alloys of higher carbon content. Therefore, a steel of this composition more rapidly develops an ability to withstand external hot tearing stresses because the film stage is traversed more rapidly.

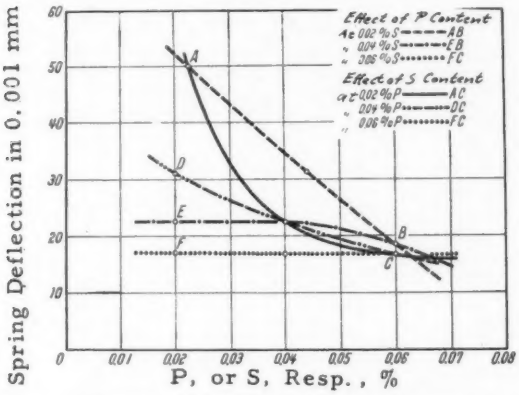


Figure 3—Decrease of hot tearing resistance with increase of a segregating constituent, the other constituent remaining unchanged (0.25 percent carbon, 0.45 percent silicon, 0.85 percent manganese cast steel)

Experiments conducted by Piwowarsky agreed with the findings of Pellini, i. e., that the temperature range of hot tearing is 55 to 90 degrees below the solidus line.

Effect of Phosphorus and Sulfur

The results of this investigation are summarized in Fig. 3. A high percentage of either sulfur or phosphorus accompanied by either a sulfur or phosphorus content varying from 0.02 to 0.06 percent causes only a small decrease in the hot tear resistance (see curve FC, Fig. 3). The greatest reduction in the hot tear resistance occurs at low phosphorus content with a change of sulfur from 0.02 to 0.06 percent (see curve AC, Fig. 3). An examination of Fig. 3 indicates that sulfur has a more pronounced effect on the lowering of the hot tear resistance.

Summary

Table 3 presents the summary of the combined effects of carbon, sulfur and phosphorus on hot tearing tendencies as determined in this study.

The resistance to hot tearing is given by the spring extension in millimeters. The greater the extension before tearing the greater the resistance to hot tearing.

The authors have agreed quite closely with previous studies on the effects of casting temperature, hot tearing temperature range, sulfur content, and phosphorus content.

The findings of this study on the effect of carbon on the hot tear resistance is contradictory to previous studies in this field.

TABLE 2—Arranged Hot Tearing Resistance as a Function of the Carbon, Sulfur, and Phosphorus Contents

% C	0.10				0.25				0.40			
% S	0.02		0.06		0.02		0.06		0.02		0.06	
% P	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06
0.001	22	18	21	10	42	31	12	19	45	32	22	17
mm	22	18	21	10	54	32	18	18	46	18	22	17

Research Project No. 44 (continued from page 13)

4—Development of new or improved molding methods, through the mechanics of sand packing, and vibration in molding.

5—A study of whether or not the property of dilatancy is important in sand molds.

Chemistry

1—Mold-metal interface reactions are more important in steel castings than is generally considered. A control of these reactions may result in the improvement of casting surfaces. It is possible that mold-conditioning (use of inhibitors) may be of as much interest to steel foundrymen as it is to magnesium casters. Iron oxide, wood flour, and graphite are examples of additives developed by trial and error. A systematic study under controlled conditions may yield useful results.

Granulated Refractories

The more abundant promising refractories such as forsterite, magnesite, chrome ore, and zircon sand are to be further studied to determine unique properties not obtainable from silica sand.

(continued next page)

T & O GROUP
QUALITY IMPROVEMENT PROGRAM

Recently each of the nine Technical and Operating Groups of the Society carried on a unified program on casting quality improvement using the Sand Evaluation Test Block as employed in Research Report No. 33 and illustrated in Fig. 1, page 6.

The three sand specimens producing the cored holes in the test block were identical in each case. All three openings were rated and then averaged. The following Table 1 lists three molding sands and four core sands that rated exceptionally well. These sands are production mixtures for miscellaneous steel foundries. Sand room temperature properties and maximum casting weights are given as well as the evaluation number.

TABLE 1—Results of T & O Quality Improvement Program

SAND MIXTURES

Composition (Weight Percent)	A	B	C	D	E	F	G
Silica Sand (AFS No.)	92.0 (AFS-65)	—	—	94	87.4	70.0 (AFS-65)	36.3 (AFS-70)
Silica Sand (AFS No.)	—	—	—	—	—	23.3 (AFS-100)	—
Zircon	—	87.8	96.0	—	—	—	58.5
Silica Flour	—	8.1	—	—	5.0	—	—
Western Bentonite	5.0	1.6	—	3.6	5.0	5.2	—
Core Oil	—	2.5	2.0	—	1.9	—	2.1
Akro	—	—	—	0.7	—	—	—
Dextrin	3.0	—	—	0.6	—	1.5	—
Cereal	—	—	2.0	1.0	1.2	—	1.0
Iron Oxide	—	—	—	—	1.5	—	—
No-Vein	—	—	—	—	—	—	2.1
Fuel Oil	—	—	—	—	3.0	—	—
Moisture	3.4	6.5	4	3.4	4.0	3.6	6.0
Properties							
Green Strength (psi)	6.8	8.0	2.8	7.7	3.4	6.5	0.65
Permeability Number	180	45	10	110	48	130	68
Dry Compression (psi)	—	—	—	—	—	—	335
Comments:	**Lightly sprayed with water, air dried over night**	**Bottom poured with 2-inch nozzle**				**Lightly sprayed with water, air dried over night**	
Core Baking (at 450°F)	—	10 hrs.	1½ hrs.	—	?	—	90 min.
Max. Casting wt. produced lbs.	2,000	8,000	20,000	2,000	1,000	2,000	1,000
Surface Evaluation† Number	8.8	8.8	8.2	8.2	8.2	8.2	7.8

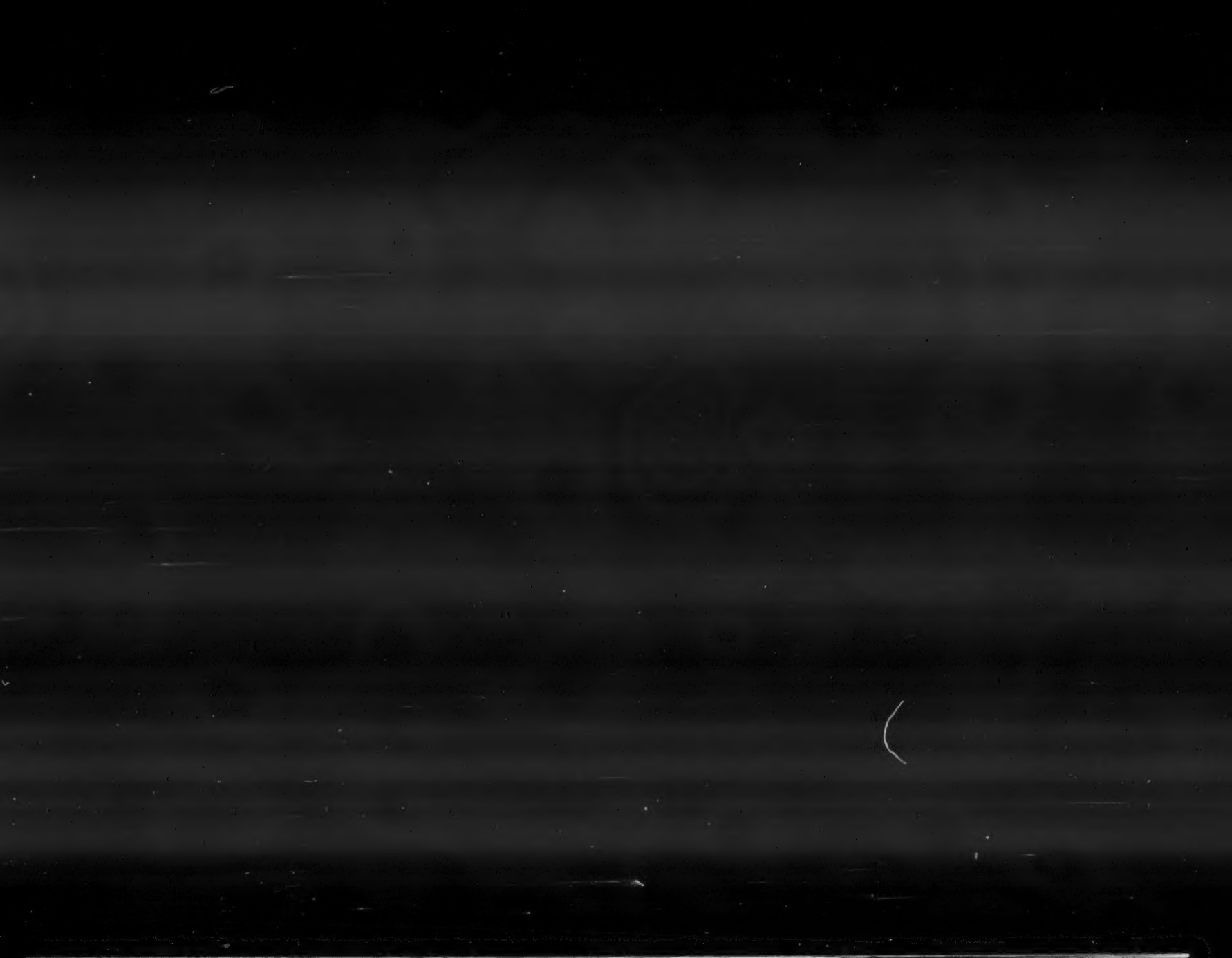
† 10 excellent; 8 good; 6 fair

Research Project No. 44 (continued from preceeding page)

Shell Molding

Some work will be continued to increase the overall efficiency of the process for extension to the larger, plain carbon steel castings.

Research Agency . . . The Foundry Division of Massachusetts Institute of Technology has been selected by the Technical Research Committee to execute the program of research. They have the personnel and the equipment to effectively carry on the program. The studies will be under the direction of Professor Howard Taylor and under the supervision of Assistant Professor Charles Reynolds.

Estimate of Time and Cost of Research . . . . The program outlined will take approximately three years for completion and the estimated cost of the research on the three-year basis is about $83,000.00.

It would be very much appreciated by the Technical Research Committee if member companies would advise the Society of any studies that they, or others, may be carrying on in the category of research which might have a bearing on the studies of Research Projects Nos. 43 and 44. The Society does not desire to duplicate work if such information can be made available to the Society.